Anomalous Tilt Preceding the Hollister Earthquake of November 28, 1974

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The occurrence of a magnitude 5.2 earthquake on November 28, 1974, near Hollister in central California, provided an excellent opportunity to test the potential of a prototype tiltmeter array as a predictive tool. Tilt perturbations on instruments near the epicenter were evident about 36 days before the earthquake and coincided with a magnetic field anomaly reported in a companion paper. The anomalous tilts systematically changed with time, reaching values as great as 7 μrad. These data are interpreted in terms of a preseismic and postseismic slip mechanism involving interaction between the San Andreas and other faults in the region, where slip on one results in a sympathetic slip on others.

INTRODUCTION

Evidence that premonitory tilting precedes earthquakes within the San Andreas fault system in central California has been previously reported [*Johnston and Mortensen*, 1974; *Mortensen and Johnston*, 1975]. These data have been used to test various earthquake precursor models [*Stuart and Johnston*, 1974] and appear to support best a creep instability model whose scale dominates that of the subsequent earthquake. With limited data the results obtained so far have been retrospective. A partial test of the data and the model is to demonstrate compatibility with simultaneous data from other crustal monitoring experiments such as geodetic strain, leveling surveys, changes in seismic velocity, and changes in the local magnetic field. The general paucity of such data for particular earthquakes has limited this comparison.

On Thanksgiving Day, November 28, 1974, at 2301 UT, an earthquake of magnitude 5.2 occurred 10 km northwest of Hollister, California. The epicenter was located on a southwest extension of the Busch fault [*Rogers*, 1967] between the Calaveras and Sargent faults. Estimates of the focal depth ranged between 4 and 7 km; the aftershock zone had vertical and horizontal dimensions of 3 and 4 km, respectively. The focal mechanism solution indicated left-lateral slip, possibly with a thrust component (W. H. K. Lee, unpublished data, 1975).

This earthquake is of particular interest because it occurred near several prototype arrays of crustal monitoring instruments. Possible precursive tilts were obtained from four instruments in an array of 14 shallow borehole tiltmeters. An array of magnetometers showed anomalous magnetic behavior preceding the earthquake at the stations nearest the epicenter [*Smith and Johnston*, 1976]. Good geodetic strain coverage was also obtained for this earthquake [*Savage et al.*, 1976].

INSTRUMENT ARRAY

The array of tiltmeters, pictured in part in Figure 1, was designed to search for crustal deformation associated with earthquakes of magnitude 2.5 and greater along an 85-km section of the San Andreas fault. The array has been in progressive stages of installation and operation since mid-1973 [*Mortensen and Johnston*, 1975]. Figure 1 shows the distribution of instruments north of Stone Canyon along the San Andreas fault in relation to the earthquake epicenter. The tiltmeter sites are generally located between 1 and 4 km from the San Andreas fault and are spaced about 6 km apart along the fault. Each tiltmeter is installed in a shallow borehole about 3 m deep [*Allen et al.*, 1973] with the exception of the Harris tiltmeter, which is located in a borehole in the floor of an inactive mine. The instrument resolution, linearity, and range are 10^{-8} rad, better than 1% (over recorded range), and 5×10^{-5} rad, respectively.

The magnetometer stations closest to the earthquake are also shown in Figure 1 and are located within a few kilometers of the Aromas, San Juan Bautista, and Harris tiltmeter sites. Details of the magnetometer array and results are discussed in a companion paper by *Smith and Johnston* [1976].

The operating tiltmeter closest to the epicenter of the Thanksgiving Day earthquake was at the Nutting site, 10.8 km to the south. The San Juan Bautista site was 11.2 km southwest of the epicenter. Unfortunately, the Sargent tiltmeter, 10.2 km from the epicenter, was not functioning during the months preceding the earthquake. Other sites were all more than 15 km from the epicenter.

RESULTS

During the months preceding the earthquake, the best records were obtained from the Aromas, San Juan Bautista, Nutting, and Harris tiltmeters. The raw N-S and E-W component records from these stations, with electronic adjustment rezeros removed, are displayed in Figure 2 along with rainfall and temperature records for the period July through December, 1974. The times of earthquakes with magnitude greater than 2.5 are noted by arrows of length proportional to the product of source dimension, depth, and inverse distance from the epicenter [*Mortensen and Johnston*, 1975]. Intermittent and less reliable data were obtained from the Mount Madonna and Tres Pinos instruments. The irregular behavior of the Tres Pinos instrument appears related to installation problems. The meter is located in a complex region less than ½ km from the Calaveras fault near its junction with the San Andreas fault. The Mount Madonna site is probably unstable because of nearby steep topography.

The general character of the tilt records during aseismic times is a smooth systematic (secular) tilt trend. A perturbation, apparently due to preearthquake distortion resulting either from a progressive failure process in the earthquake source zone or from a process that subsequently produces the earthquake, or perhaps both, is most clearly seen on the San Juan Bautista record. Here less than 2 μrad of tilt was registered for the aseismic period from July through mid-October. On October 22 the San Juan instrument rather suddenly began tilting at a rate averaging ½ μrad per week and continued until

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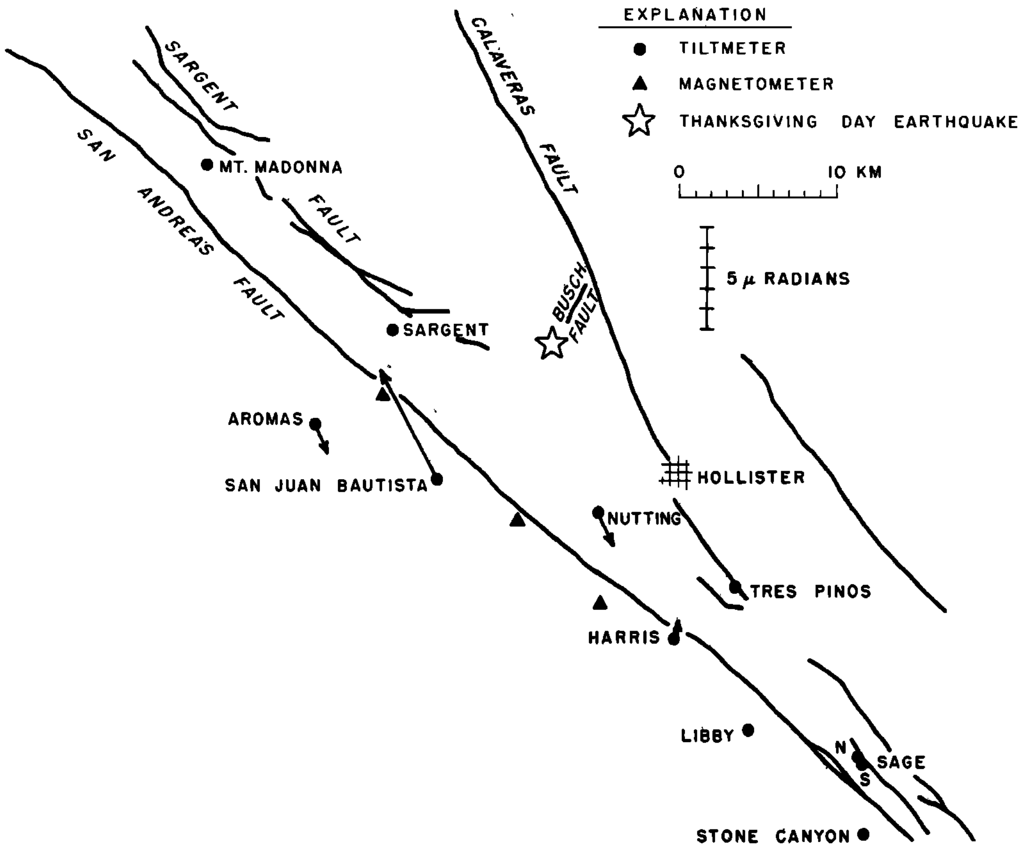

Fig. 1. Simplified fault map near Hollister, California, showing location of tilt sites, magnetometer sites, and epicenter of the Thanksgiving Day earthquake $M_L = 5.2$. Residual tilt vectors are plotted at the four operating tilt sites nearest the Thanksgiving Day earthquake epicenter.

the instrument power failed 6 days before the earthquake. There were no obvious meteorological or other nontectonic effects that could have produced this tilting.

A perturbation, although less convincing, can be identified starting about November 10 on the Aromas record. The Harris and Nutting records also show slight changes in trend on about November 8 and October 21, respectively. These perturbations can be isolated by removing the general secular trends from the records. The residual N-S and E-W tilts, accumulated from the time the changes in trend were first identified to the time of the earthquake, were combined to produce the maximum residual tilt vectors at each instrument site plotted in Figure 1. It is interesting to note that the 5 months preceding the earthquake were unusually quiet seismically along the section of the San Andreas fault from Libby Ranch north, and yet there were high tilt rates of as much as 3 μrad/month at the Harris Ranch and Nutting Ranch sites, which are normally comparatively stable.

The change in azimuth and amplitude of tilt can be plotted for each of the four sites of interest. However, an obvious problem with this type of plot is that for periods when the tilt rates are small, the azimuth is unstable, as it is at San Juan Bautista before October 22.

Raw records from each operating tiltmeter installation on the day of the earthquake are shown in Figure 3. The slight inflections that appear a few hours before the earthquake on some of the records, such as those on the record from the Sage South instrument, are tides and/or diurnal thermoelastic effects. After the arrival of the seismic wave some instruments were offset with respect to their preearthquake values. Table 1 lists the amount of these offsets for the N-S and E-W tilt components at each instrument site. These offsets are plotted as vectors in Figure 4. The agreement between the Nutting, Tres Pinos, and Sage sites (all on the northwest side of the San Andreas fault) is evident. Offsets at stations on the southwest side of the San Andreas fault have no simple pattern. The magnitude of the offsets diminishes markedly south of the Sage Ranch site. Curiously, the offset was as large at the Sage site, 32 km south of the epicenter, as it was at the Nutting station, closest to the earthquake. This may be partly due to strain amplification in the hill at the Sage site, or the amount of offset may depend on the static strain field at the site at the time of the earthquake, or the agreement may be coincidental and the offsets due to site response to the shaking, or all of the above may contribute. Coseismic slip on the San Andreas, reported by R. O. Burford (personal communication, 1975), extended from north of San Juan Bautista, where the creepmeter recorded a 1.3-mm offset, to the Cienega Winery between the Harris and Libby tiltmeter sites, where a very small creep event (≤0.1 mm) was observed.

Another interesting aspect of the tilt records at the time of the first seismic wave arrival is an exponential-like recovery from an initial tilt offset. This can be seen most dramatically on the Nutting and Sage records in Figure 3. The decay is less obvious but still present in the other records. This apparently anelastic recovery has been previously observed at the times of many small to moderate local earthquakes but never for distant earthquakes. In the Nutting instrument the 20-s low-pass filter had been switched off during the time before and after the earthquake, while in the Sage instrument the output low-pass filter was in operation. At all other stations whose records appear in Figure 3, the low-pass filter was in the 'off' position.

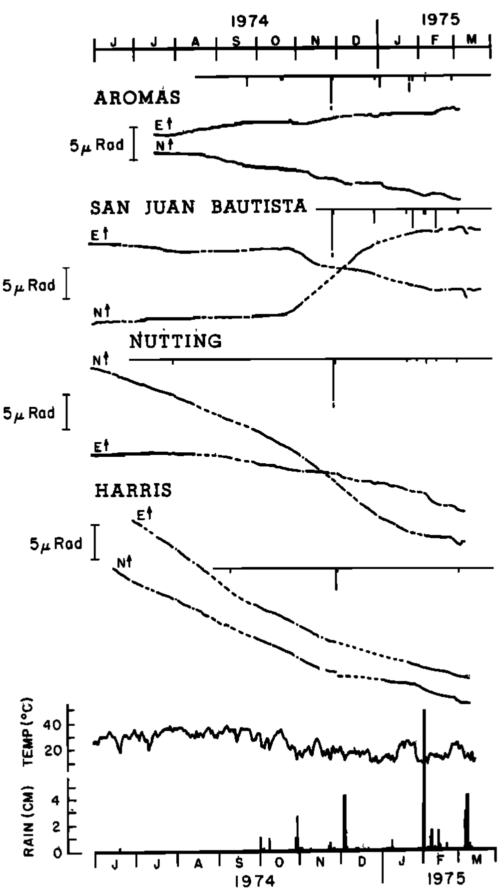

Fig. 2. Raw records from the four operational tilt sites nearest the Thanksgiving Day earthquake epicenter. Local earthquakes near each site are plotted above each record as vertical lines of length proportional to source dimension, depth, and inverse distance. Rainfall and temperature in the area of the tilt array are shown in the bottom plot. Dashed lines connect record sections where the on-site recorder failed but the instrument zero was not lost.

The possibility that this decay is of instrumental origin has not yet been absolutely ruled out. At certain frequencies higher than 1 Hz, rectification due to a pressure gradient effect across the bubble is known to occur in the bubble level sensor. However, since the observed decay commonly persists for much longer periods than the coda length of the earthquakes and the decay has never been observed for large teleseismic events with comparable surface and body wave amplitudes but less high frequency content, the effect is most probably anelastic behavior in the ground. Responses of similar form have also been observed at the times of nearby earthquakes in this area on the records of mercury liquid level tiltmeters, strainmeters, and gravimeters.

The question still remains whether the observed tilts could be of nontectonic origin. Rainfall and variations in temperature are the principal sources of nontectonic noise-contaminating tilt observations. The effects of cracks, fractures, complex geology, topography, heterogeneous stress fields, groundwater movement, and variations in rock properties are reasons to expect spurious tilt response with temperature, pressure fluctuations, and rainfall. The techniques used to minimize these effects in U.S. Geological Survey tiltmeter and strainmeter sites are discussed by *Johnston and Mortensen* [1974] and *Mortensen and Johnston* [1975]. The degree to which these precautions are successful can be determined at each site.

Contributions to an annual tilt cycle might be expected from thermal effects on the site and instrument and from rainfall, since in the area of installation, rain ordinarily occurs only during the winter. An apparent annual cycle is observed at Libby. However, because thermal effects of instrumental origin should be common to all meters and since this is the only site where a clear annual cycle is observed, this is probably a site effect. The gross tilts from temperature and rainfall appear, in general, to be dominated by tilts of tectonic origin. A shorter-term change in average surface temperature occurs in October. However, other temperature changes with similar amplitudes and time scales occur in June, July, and January without noticeably perturbing the records.

A catalog of tilt response at each site to rainfall amount, rate, and previous history has been compiled to determine the degree to which spurious tilts are caused by rainfall. Preliminary results of that analysis indicate that at the tilt sites having symmetric gentle topography and good drainage, moderate rainfall of up to 2.5 cm produces no observable response at the 10^{-7} level. For increased rainfall the amplitude of tilt response depends partly on the amount of rainfall but more importantly on the length of time over which it falls. At the San Juan Bautista site, for example, the very heavy 13.5 cm of rainfall of February 1 and 2, 1975, produced little response, while the 9.5 cm of rainfall spanning the second week of March produced an off-scale tilt of several microradians. The time of recovery from a rainfall-induced tilt to the previous secular trend at a site depends roughly on the amount of rainfall and appears to be governed by a diffusion process. At the Nutting site, for example, the tilt returns to its previous trend within 2 days following a rainfall of 3.8 cm. The direction of tilt in response to rainfall appears to be consistent at each tiltmeter site.

In looking for rainfall effects, close inspection of the San Juan Bautista record in Figure 2, for example, indicates that (1) the changes in tilt trend that determine the start of the tilt anomaly occurred several days before the start of rain at the end of October, (2) the earlier rainfall in October, although of much smaller amount, produced no perceptible change in tilt, (3) later periods of rainfall, even up to 13.5 cm in the first week in February, did not produce as dramatic a change in tilt as that which occurred from mid-October to mid-December, the time span that covers the November 28 earthquake, and (4) the change in tilt during the anomalous period differs in direction from the change induced by the heavy rainfall of early March. It appears unlikely therefore that the major changes in this record could be attributed to rainfall effects.

The position is less clear for the other records where tilt anomalies are not so obvious. For example, in the Aromas record an argument can be made for a rain-induced tilt at the end of October, although it is curious that the heavy rainfall in early December did not produce as large an effect and the earlier rains in October produced no perceptible effect.

DISCUSSION

Anomalous tilting with a time scale of more than 30 days and an amplitude of 7 μrad occurred most convincingly on the San Juan Bautista tiltmeter 11.2 km from the epicenter of a magnitude 5.2 earthquake both prior to and following the earthquake. This tilt was measured near the point on the San Andreas fault where the extension of the rupture zone would intersect the fault. Tilts marginally above the noise were ob-

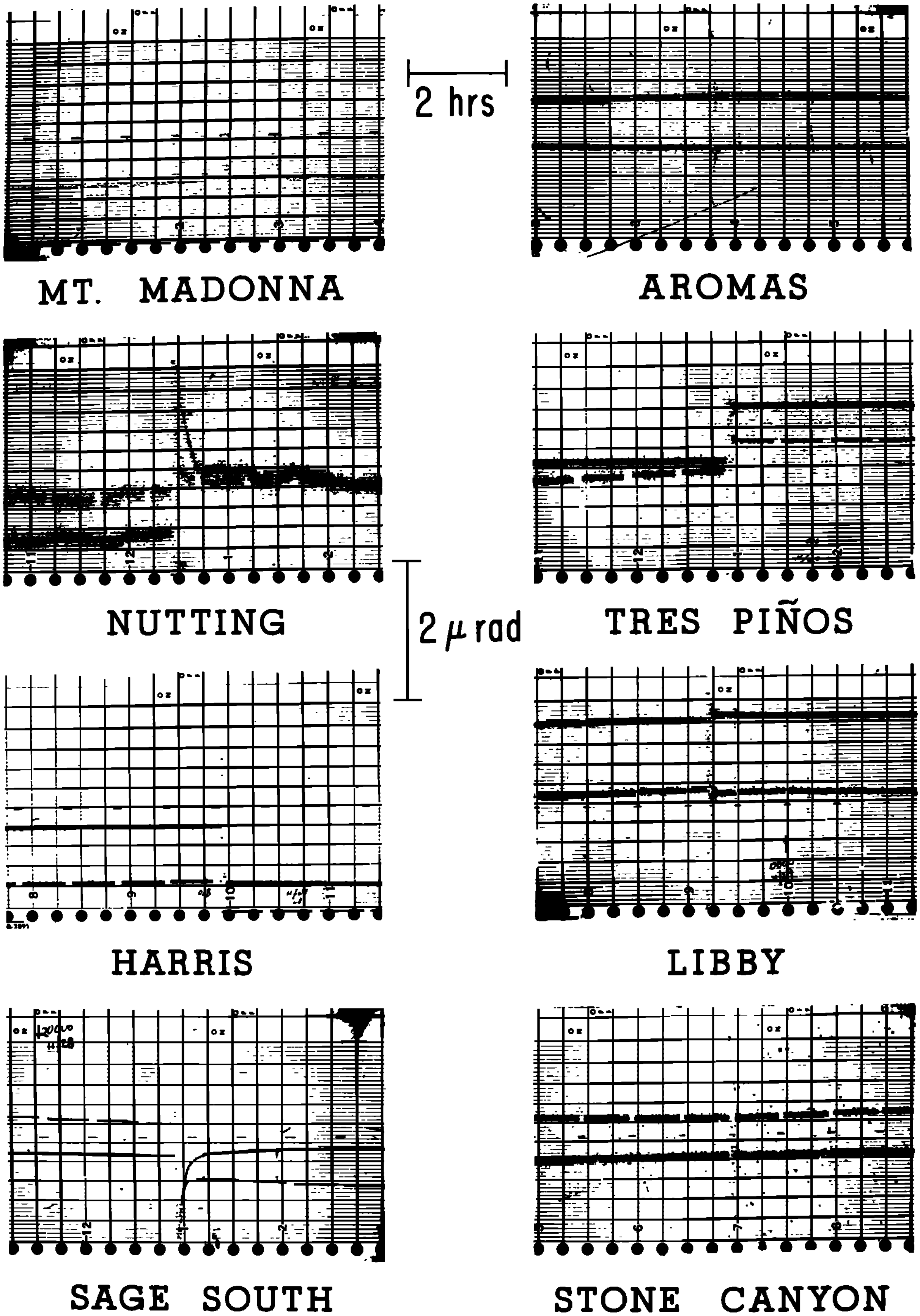

Fig. 3. Raw records at eight tilt sites at the time of the Thanksgiving Day earthquake.

TABLE 1. Tilt Offsets at the Time of the November 28, 1974, Earthquake

Station	N-S, μrad	E-W, μrad	Decay Time, min	Filter
Mount Madonna	~+0.07	?	?	Off
Sargent	...	...	...	...
Aromas	0.0	+0.059	~13	Off
San Juan Bautista	...	...	...	...
Nutting	+0.97	+0.16	40	Off
Tres Pinos	+0.78	+0.47	~16	Off
Harris	−0.85	~−0.41	~15	Off
Libby	~+0.09	~−0.08	~17	Off
Sage South	+0.84	+0.059	40	On
Stone Canyon	0.0	0.0	~ 0	Off

served on the three other tiltmeters closest to the earthquake. These tilts would not be considered important were it not for their coincidence in time with the larger San Juan Bautista anomaly.

The most important question concerning these and companion magnetic and geodetic data is whether general physical implications regarding precursor models and fault behavior in this region can be developed. It is probably a unique circumstance that these three low-frequency data sets were obtained so close to an earthquake of this magnitude. In this region also, the two main classes of earthquake precursor models, dilatancy fluid diffusion, and creep instability, have recently been tested [*Stuart and Johnston*, 1974]. The preliminary results tended to support the creep instability process. For the tilt data reported here it is difficult also to fit the symmetric tilt field and the tilt time dependence suggested for the dilatancy precursor models such as those proposed by *Nur* [1974] and *Kisslinger* [1975].

The simplest and most obvious creep instability model involves precursive left-lateral slip in the region around the earthquake hypocenter. However, the moment required to generate the observed tilt amplitudes exceeds 10^{25} dyn cm, and the directions of tilt are generally opposite to those observed. Also, there are no apparent corresponding geodetic strain changes at this location [*Savage et al.*, 1976].

A source much closer to the tiltmeters is necessary to explain the large tilt amplitudes, although this implies a complex fault interaction process where slip on different faults results in loading, sympathetic slip, and earthquakes on the Busch fault. It is possible that the large amplitudes are due to some unknown mechanical or site amplification effect. The best fit for a source on the San Andreas is obtained for right-lateral aseis-

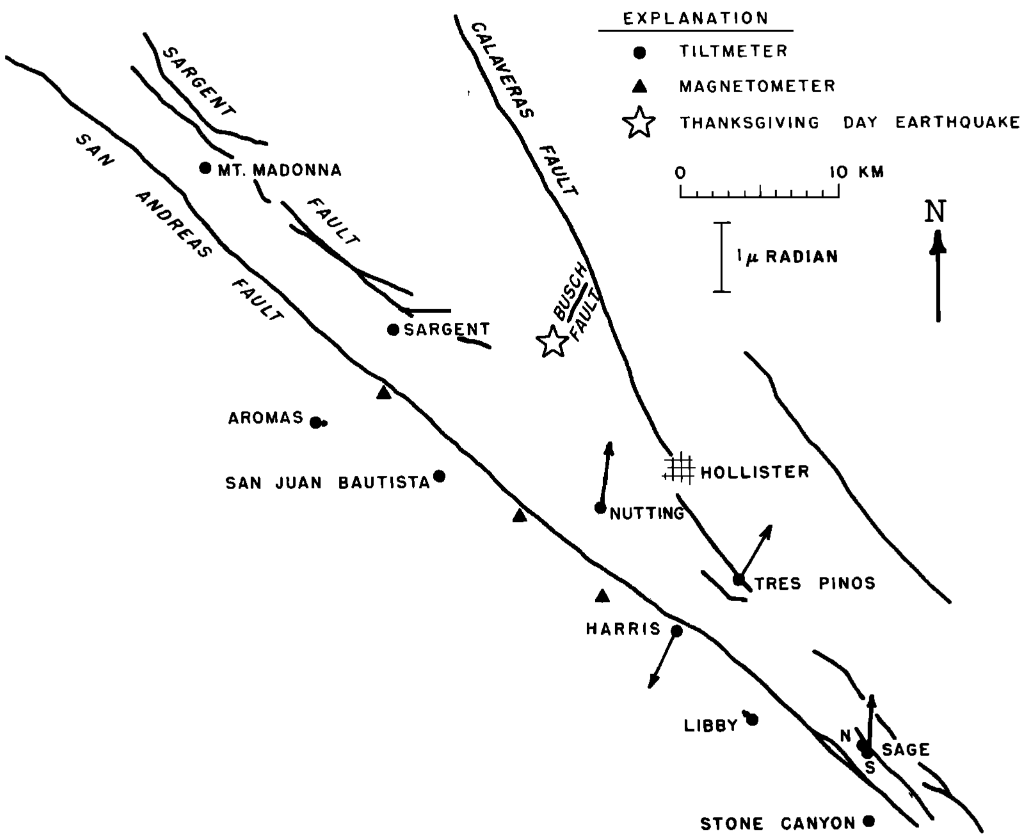

Fig. 4. Vectors representing permanent tilt offsets at each tilt site at the time of the Thanksgiving Day earthquake. Table 1 gives component values of offsets, times required for instruments to settle to new tilt position, and status of the 20-s output filter.

mic slip approximately 5 km deep and about 3 km south of the San Juan Bautista tiltmeter. This is roughly coincident with the location of the source required to explain the magnetic anomaly data [*Smith and Johnston,* 1976]. The slip moment could be as low as 10^{23} dyn cm, which is insufficient to be detected as a geodetic strain change.

If the observed tilt signals do result from right-lateral aseismic slip on the San Andreas fault, which contributed incrementally to the stress on the Busch fault but was not, in this case, directly related to the earthquake mechanism, such tilt signals might also be expected without an accompanying earthquake. The possibility that the tectonic evolution of this region is a consequence of interrelated fault behavior [*Johnston et al.,* 1975] is the subject of a different study.

Tilt array data in this region are still relatively new, and it is fortunate that several other types of strain measurements are being made simultaneously. Confidence and expertise in the use and interpretation of these data will develop as the implications and conclusions drawn are tested in other independent data sets. The November 28 earthquake was the largest in this region since 1972 and was coincident with the largest tilt and magnetic anomalies since the start of operation of the present arrays in mid-1973. It provided the first real opportunity for comparison of simultaneous observations; techniques; and ideas related to the prediction of earthquakes in this region.

Acknowledgment. We thank the staff of the University of California, Berkeley Seismographic Station, for the opportunity to make tilt measurements in the San Andreas Geophysical Observatory, Harris tunnel.

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(Received December 30, 1975;
revised March 5, 1976;
accepted March 5, 1976.)